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MODELING EXPLOSIVE CLADDING OF METALLIC LINERS TO GUN TUBES

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14. ABSTRACT

A computational investigation of explosive cladding of refractory metal based materials was conducted in support of the Full Combat Systems Durable Gun Barrels Manufacturing Technology Objective (MTO) and Chromium Elimination Strategic Environmental Research and Development programs. The objective of the effort was to develop and demonstrate physics based modeling for explosive barrel cladding process design and optimization. The effort was focused on cladding modeling development, cladding process design, and optimization. The effort applied high rate continuum modeling to physically model the process of barrel liner cladding. High explosive equations of state were being developed for the unique low density, low detonation velocity explosives used in the cladding process. A multi-scale dynamics approach was taken to address macro-scale liner cladding, as well as micro-scale clad welding dynamics. Process modeling included computational investigation of momentum trap geometries to avoid gun deformation during the cladding process.

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CONTENTS

FIGURES

INTRODUCTION

The Army is investigating several different methods of extending gun barrel service life and eliminating chromium from gun barrel processing. Gun barrel erosion and wear are the major determinants in the service life of most Army guns. Barrel erosion and wear are becoming increasingly more important issues with the push to use higher performance propellants with higher flame temperatures. One of the methods being developed to reduce barrel wear and erosion is the cladding of refractory metal based alloys to the inside of gun barrels. TPL, Inc. has successfully bonded refractory metal liners to the inside surface of the 25-mm M242 Bushmaster barrel using low-detonation velocity explosives (ref. 1). The current ongoing experimental development includes cladding various refractory metal based alloys to gun barrel step test configurations (ref. 2). In support of this work, an ongoing computational investigation of explosive cladding of refractory metal based materials (ref. 3) was conducted. Whereas, some simplified analytic modeling of explosive welding was investigated (refs. 4 through 6), very little physics based continuum modeling for explosive barrel cladding process design and optimization has been completed to date. Therefore, the objective of this computational effort was to apply high rate continuum modeling to physically model the process of barrel liner cladding. The FY04 effort was focused on cladding modeling development; whereas, the FY05 effort was focused on cladding process design and optimization. High explosive equations of state are being developed for the unique low density, low detonation velocity explosives used in the cladding process. A multi-scale dynamics approach was taken to address macro-scale liner cladding, as well as micro-scale clad welding dynamics. Process modeling included computational investigation of momentum trap geometries to avoid gun deformation during the cladding process.

EQUATION OF STATE

The explosives used in this cladding effort have very low energy levels compared to traditional military explosives. A variety of explosive compositions were experimentally investigated. A final composition, designated BondEx-D2 was down-selected for the gun cladding process. Traditionally, high explosive equations of state are verified and/or calibrated using standardized copper cylinder expansion tests (ref. 7). Although this testing was planned, no such testing existed for BondEx-D2. For this reason, an alternate empirical approach was adopted to provide an equation of state. Cooper (ref. 4) developed an empirical relationship to estimate Gurney energy, $\sqrt{2E}$

$$\sqrt{2E} = D/2.97 \tag{1}$$

where D is the detonation velocity of the explosive. Using the experimental D for the Chapman-Jouguet state and assuming the empirical $\sqrt{2E}$ is valid at seven volume expansions, a Jones Wilkins Lee (JWL) equation of state was parameterized using nonlinear optimization (ref. 8) and scaling the empirical $\sqrt{2E}$ for other volume expansions based on TNT. The JWL equation of state is

$$P = \sum_i A_i\left(1 - \frac{\omega}{R_i V*}\right)e^{-R_i V*} + \frac{\varpi E}{V*} \tag{2}$$

where P is pressure, V^* is relative specific volume, and E is internal energy. The resulting predicted cylinder test result is presented in figure 1.

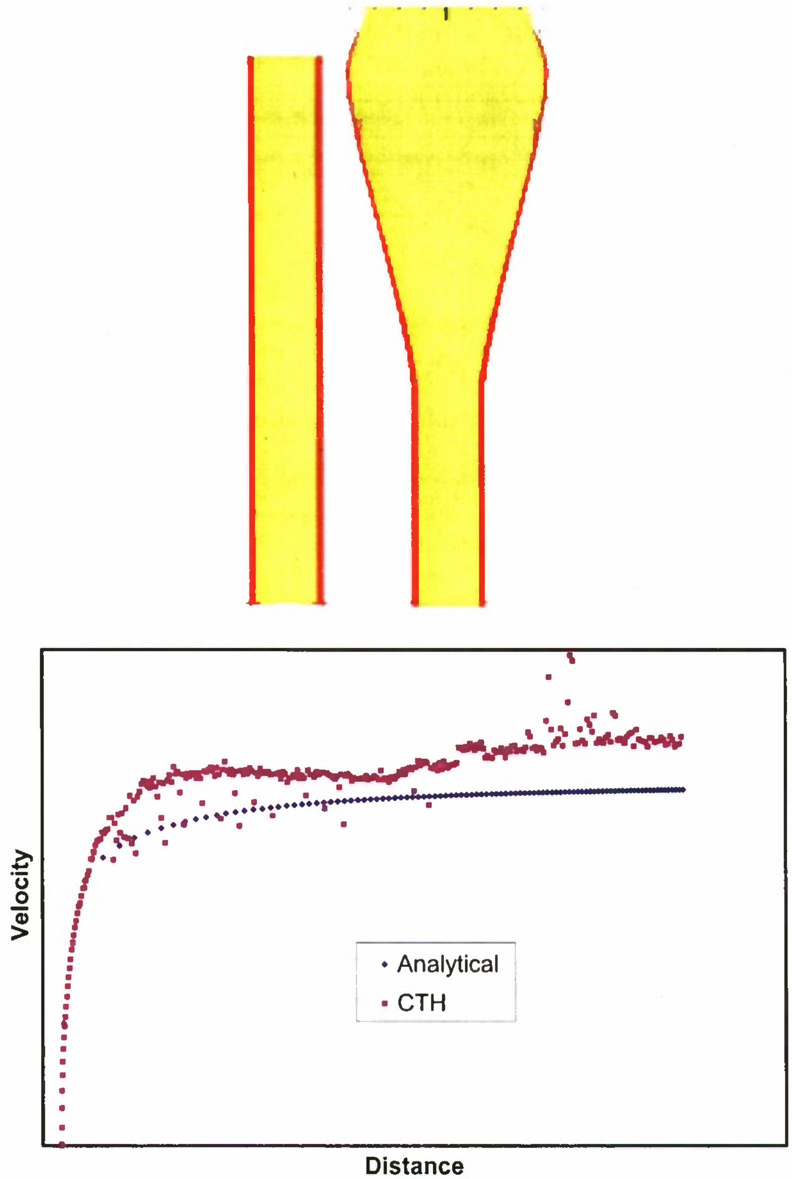

Figure 1
BondEx-D2 predicted standard copper cylinder expansion test result using CTH

MACRO-SCALE CLADDING MODELING

Ongoing experimental development includes cladding various refractory metal based alloys to gun barrel step test configurations. In support of this work, a macro-scale computational investigation of explosive cladding mechanics using refractory metal based materials is being conducted. Modeling of a gun barrel step test configuration was completed using the Zerilli-Armstrong material model for pure refractory metal and a refractory metal alloy as the cladding tube. The steel step test configuration was modeled using the Zerilli-Armstrong model for ASTM 4340 steel. Figure 2 presents cell thermo hydrodynamics (CTH) material plots of the macro-scale modeling of a gun barrel step test configuration. Figure 3 presents the calculated velocity versus radius history for the cladding tube outside surfaces corresponding to the individual steps. It is important to note that the cladding tube is strongly accelerating at the time of cladding impact for all the steps modeled. This indicates that a traditional Gurney assumption for final tube velocity is not accurate, as a final asymptotic velocity was not achieved for the geometries investigated. Figure 4 presents a plot of the calculated velocity versus angle for the cladding tube outside surfaces corresponding to the individual steps. This result indicates that the angle versus velocity relationship agrees well with traditional Taylor angle relationship (ref. 5)

$$v = 2D\sin\frac{\theta}{2} \tag{3}$$

where v is the velocity and θ is the angle of the cladding tube. Another interesting result of the modeling is that the pure metal velocity histories are virtually identical to velocity histories of the alloys of those metals for the cladding cylinders. This is probably due to the relatively high charge to mass ratios of the cladding tubes, so that the strength properties of the cladding tubes did not significantly affect the velocity histories. This macro-scale modeling can now be applied in order to design other geometries that reproduce desirable impact velocities and impact angles that have been successful in experimental studies.

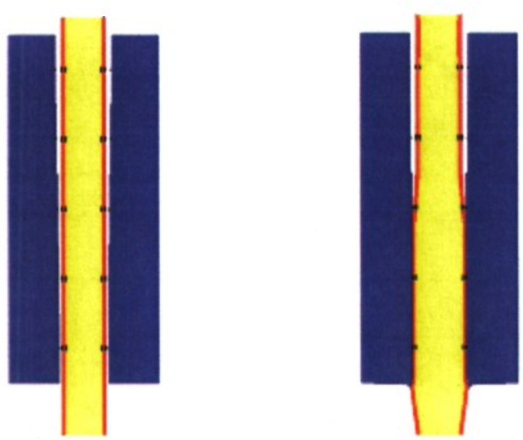

Figure 2
CTH material plots of the macro-scale modeling of a gun barrel step test configuration
[Initial conditions (left) and during explosive cladding (right)]

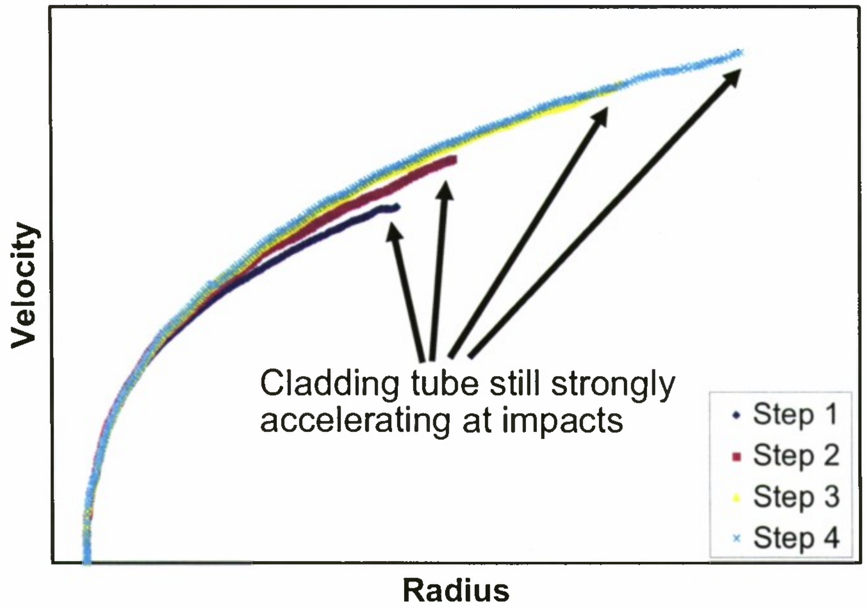

Figure 3
Calculated velocity versus radius history for the cladding tube outside surfaces corresponding to the individual steps

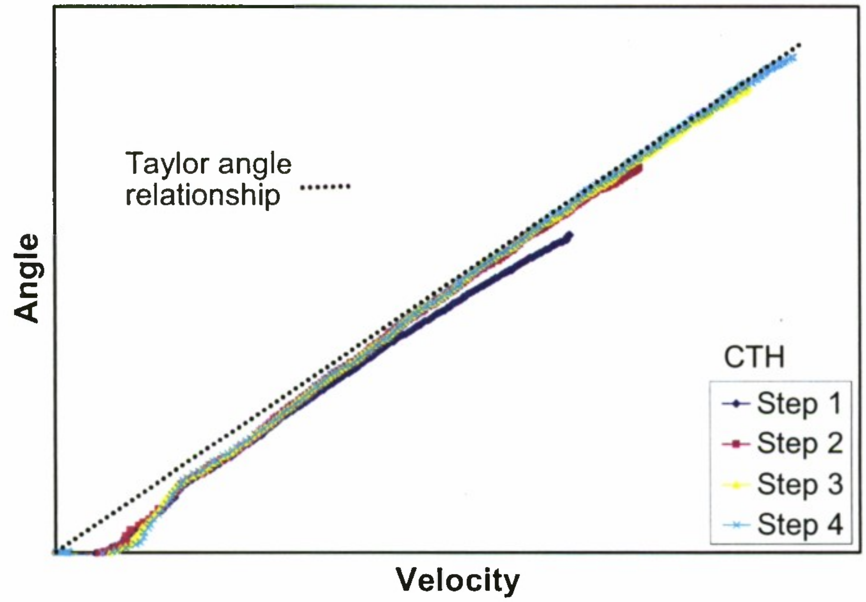

Figure 4
Calculated velocity versus angle for the cladding tube outside surfaces corresponding to the individual steps

MICRO-SCALE CLADDING MODELING

In an effort to predict the quality of welding strength, micro-scale cladding modeling was attempted using CTH with the relatively new automatic mesh refinement routines in order to produce fine resolution modeling at the cladding surface. This methodology produces finer resolution Eulerian sub-meshing in predefined areas. Using this technique, a mesh resolution of 0.1 mm was achieved. Figure 5 presents modeling results of the cladding interface surfaces corresponding to the individual steps. Figure 6 presents a polished experimental step test specimen and associated etched micrograph results for the same interfaces. The computationally predicted wavelengths are significantly longer than the experimental results. Additionally, the experimental results clearly show regions of mixed or alloyed refractory metal with the steel. This physical effect cannot be reproduced using the current CTH modeling approach.

Step 1

Step 2

Step 3

Step 4

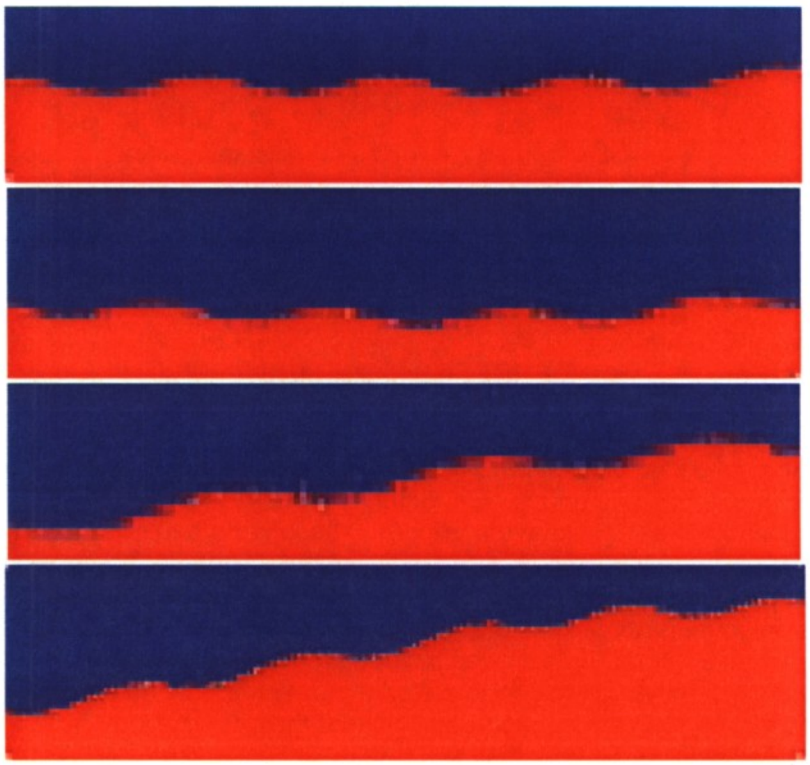

Figure 5
Modeling results of the cladding interface surfaces corresponding to the individual steps
[Blue (top) is steel and red (bottom) is refractory metal]

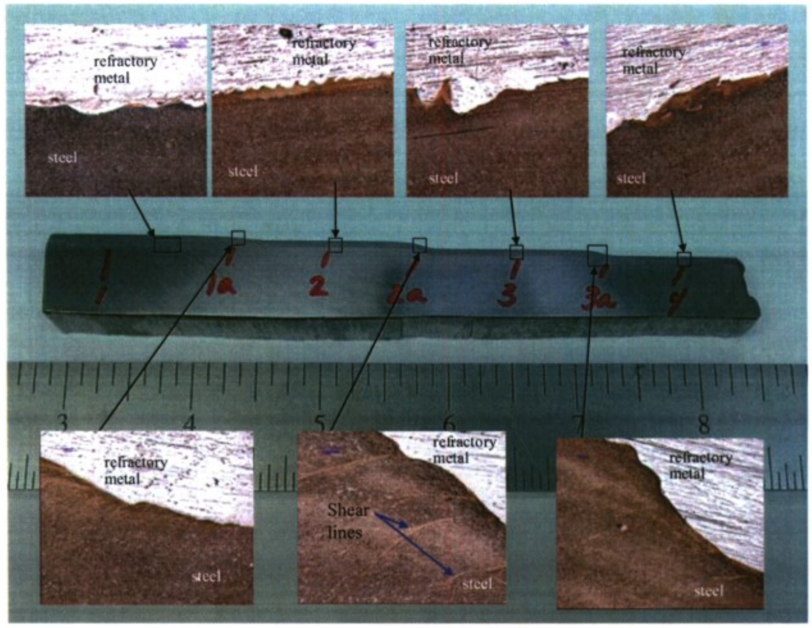

Figure 6
Polished experimental step test specimen and associated etched micrograph results for the same interfaces

PROCESS MODELING

As part of the computational gun cladding process modeling, methods are being investigated to prevent gun barrel deformation as a result of the cladding process. In particular, the thinner muzzle end section of the gun barrel is potentially susceptible to deformation due to the explosive event. For this reason, the barrel is contained in a confinement arrangement known as a "momentum trap." A material model was developed for the primary momentum trap material. Figure 7 presents modeling of a momentum trap configuration without a gun muzzle endplate; whereas, figure 8 presents similar modeling of a geometry that does include a gun muzzle endplate. The computational results clearly show that the endplate configuration produces considerably less potential deformation than the configuration without the endplate.

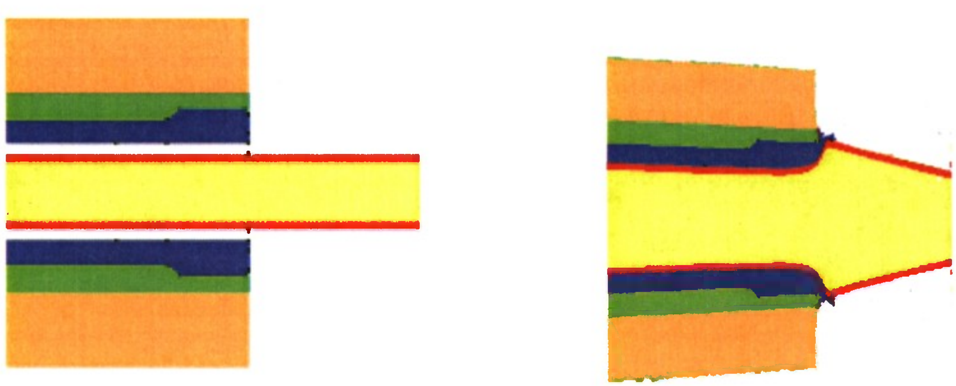

Figure 7
Modeling of a momentum trap configuration without a gun muzzle endplate

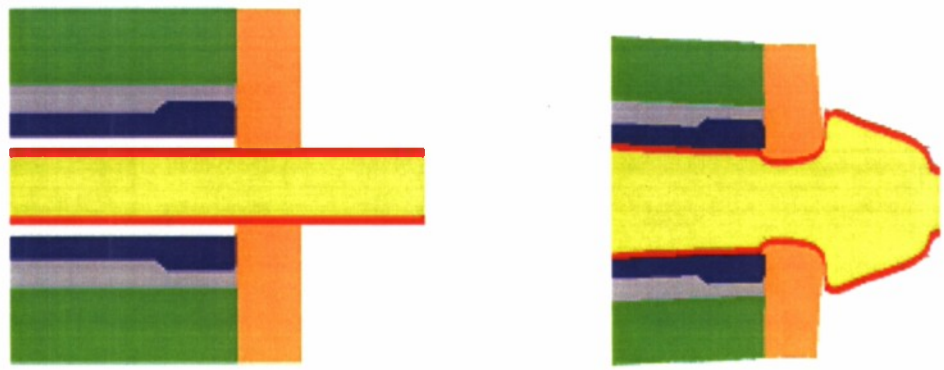

Figure 8
Modeling of a momentum trap configuration with a gun muzzle endplate

SUMMARY

A multi-scale dynamics approach was taken to address macro-scale liner cladding, as well as micro-scale clad welding dynamics. The macro-scale modeling results indicate that traditional Gurney formulation will over predict cladding tube velocities, as the cladding tube is still accelerating rapidly at the time of cladding impact. In contrast, the traditional Taylor angle relationship is shown to be very accurate. The macro-scale modeling capability can now be used to design other cladding configurations that reproduce successful experimental cladding impact velocities and angles. Micro-scale modeling to date does not agree well with observed welding characteristics. Process modeling currently includes the development of appropriate gun confinement or momentum trap geometries to prevent potential gun deformation caused by the explosive cladding event. Ongoing work includes the experimental cylinder test characterization and equation of state validation of cladding explosives, as well as characterization of high rate constitutive properties for the high rate modeling of gun steels.

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